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EFFECT OF NONLINEAR AIR FILTRATION ON THERMAL REGIME OF ROCK-FI--ETC(U)
JAN 77 N A MUKHETDINOV

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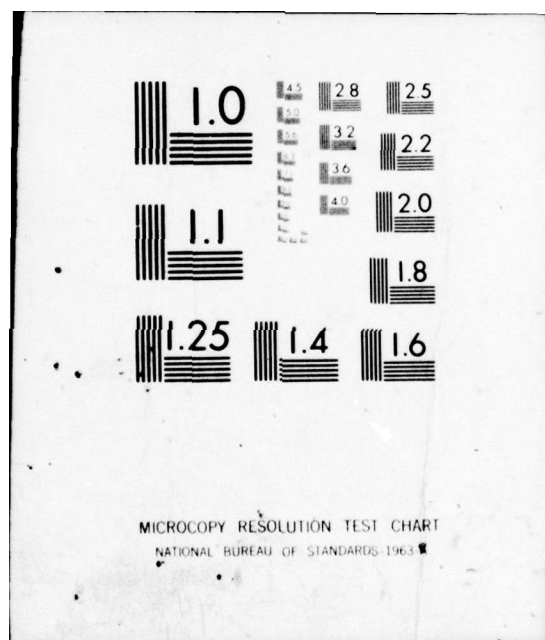
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EFFECT OF NONLINEAR AIR FILTRATION ON THERMAL REGIME OF ROCK-FILL DAM

N.A. Mukhetdinov

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EFFECT OF NONLINEAR AIR FILTRATION ON THERMAL REGIME OF ROCK-FILL DAM

[Moscow] IZVESTIYA VSESOYUZNOGO NAUCHNO-ISSLEDOVATEL'SKOGO INSTITUTA
GIDROTEKHNIKI in Russian Vol 96, 1971 pp 205-217

[Article by N. A. Mukhetdinov, engineer]

[Text] Research on natural convection in porous media with a vertical temperature gradient has established that air (fluid) movement occurs at a certain critical difference in temperatures [1, 2]. A definite velocity and regime of the air current arise in a porous medium for each difference in temperatures beyond the critical point. It is considered that the laminar current regime occurs in porous media if the Reynolds number $Re < 10$, while the regime is turbulent if $Re \geq 7,000$ [3]. In the range of Reynolds numbers $Re = 10-7,000$ air movement corresponds to what is called the transitional current regime with local, not general, turbulence of the current between particles.

We know that for the laminar regime of an air current (or fluid) losses of pressure are proportional to velocity in the first degree, while for the turbulent regime it is the second degree.

1. Losses of Pressure with Air Filtration Through Porous Media Under Conditions of Natural Convection

It has been proven both theoretically [4] and experimentally that losses of pressure in porous media for any Reynolds number can be described by the following two-term formula:

$$\frac{dp}{dy} = \frac{\mu}{k} w + b_{in} w^2, \quad (1)$$

where dp/dy are pressure losses, μ is the modulus of dynamic viscosity of the air, k and b are test coefficients which depend on the type of porous medium and the physical properties of the air, and w is the rate of air filtration.

In formula (1) the first term characterizes the influence of viscosity and the second is the influence of inertial forces, which have been

studied by many investigators [3, 5, 6]. A comparison of the results of different investigations shows that the values of the parameters k and b_0 fluctuate in a broad range. At the same time to receive analytic calculation formulas for determining pressure losses requires the introduction of so many simplifying assumptions that the result is in large part useless [3]. In calculations, therefore, empirical and semiempirical expressions for parameters k and b_0 which generalize experimental material are usually used. An acquaintance with existing recommendations showed that the aforementioned coefficients have not yet been determined for conditions of natural convection in large-pore media.

We carried out special experimental investigations to determine pressure losses and the filtration regime in large-pore media. The experiments were conducted under laboratory conditions with air at above-freezing temperatures.

The experimental installation was a thermally insulated tube (internal diameter of 87 centimeters, one meter long) with a steel plate bottom (five millimeters thick) containing 20-millimeters holes evenly distributed over the entire area of the bottom. An electric heater was set in the lower part of the tube. The upper part of the unit ended in an exit cone with an angle of 90 degrees at the apex and an opening 9.5 centimeters in diameter. For the experiment the tube was loaded with rocks and thermocouples were set in the pores every 50 centimeters (five thermocouples in each of three ranges), then the exit cone was secured hermetically to the tube. The temperature in different layers of the tube was recorded by the thermocouples with a precision of 0.3 degrees C. while air velocity at the exit of the exit cone was measured by a vane anemometer with a sensitivity threshold of 0.15 meters per second.

Readings were taken every 30 minutes. The air in the base of the tube was heated by an electric heater. Owing to the uneven distribution of air temperatures in the porous medium, the warm air rose, giving part of its heat to the medium loaded in the tube (the rock).

The electric heater switched off after the air in the lowest measurement range reached a temperature of 100-120 degrees C. Continued air movement in the tube occurred entirely through difference between the pore temperature and outside temperature. The data were processed on the assumptions that air was evenly distributed in the tube on the cross-section and that the lifting force was proportional to pressure losses at any moment in time. The latter can be derived from the following reasoning.

When air moves under the influence of a lifting force, equation (1) for the axis coinciding with the direction of the force of gravity appears as follows:

$$\frac{dp}{dy} = \frac{\mu}{k} w + b_0 w^2 - \gamma \beta m \Delta T, \quad (2)$$

where γ is the specific weight of the air, β is the dilation of the air, m is porosity, and ΔT is the temperature difference between pore and outside air.

Let us integrate equations (1) and (2) for the length of the porous layer in the experimental unit, considering parameters μ , k , and b_0 and the rate of filtration w to be constant.

As a result we obtain for equation (1):

$$(p_{bx} - p_{bix})_{\text{nat. k}} = \frac{\mu}{k} wH + b_0 w^2 H; \quad (1')$$

and for equation (2)

$$(p_{bx} - p_{bix})_{\text{c. k}} + \gamma \beta m \Delta T_{cp} H = \frac{\mu}{k} wH + b_0 w^2 H, \quad (2')$$

where p_{bx} is the air pressure at the input of the tube, p_{bix} is the same at the outlet, $(p_{bx} - p_{bix})_{\text{nat. k}}$ is the pressure difference with forced convection, $(p_{bx} - p_{bix})_{\text{c. k}}$ is the same for natural (free) convection, and W is the elevation of the layer of porous medium.

The right parts of equations (1') and (2') can be made equal in experiments by selecting the corresponding difference of pressures or lifting force. In this case, equating the right and left parts of the equations (1') and (2') we obtain:

$$(p_{bx} - p_{bix})_{\text{nat. k}} = (p_{bx} - p_{bix})_{\text{c. k}} + \gamma \beta m \Delta T_{cp} H. \quad (3)$$

When the cause of air movement is the difference in temperatures of the pore and outside air the condition $p_{bx} \approx p_{bix}$ is met with adequate precision. It then follows from equation (3) that

$$\frac{(p_{bx} - p_{bix})_{\text{nat. k}}}{H} = \gamma \beta m \Delta T_{cp}$$

that is, there is a formal coincidence of the pressure gradient, for forced movement with a lifting force in equation (1) and for natural convection in equation (2).

The regime of an air (fluid) current in a porous medium is determined by a diagram of the relationship between the coefficient of hydraulic resistance in filtration (f_p) and the Reynolds number [7].

In processing the results of our tests the coefficient of resistance (f_p) and the Reynolds number (Re) were computed according to formulas [6, 7]:

$$f_p = \frac{g \beta m \Delta T_{cp} d m^3}{(1 - m) w^2}; \quad (4)$$

$$Re = \frac{w d}{6 \alpha \nu (1 - m)}. \quad (5)$$

where g is the acceleration of the force of gravity, d is the effective diameter of the cleavages of the porous medium, α is the ratio of a cleavage surface to the surface of a sphere with diameter d , β is the kinematic viscosity coefficient of the air, $\Delta T_{cp} = \theta_{cp} - t_{\text{map}}$ is the average temperature difference, t_{map} is the outside temperature of the air, and θ_{cp} is the average air temperature in the pores inside the experimental device.

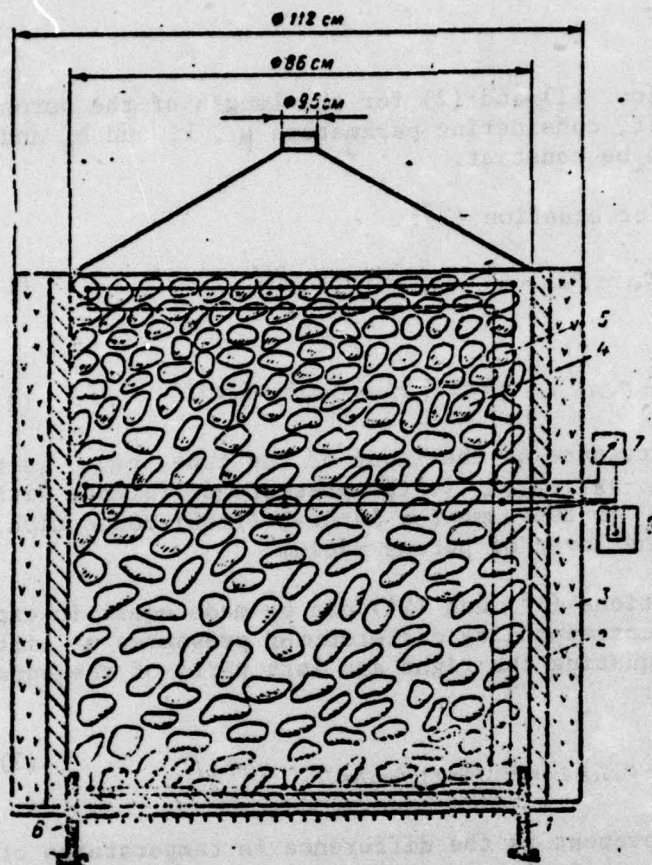


Figure 1. Diagram of the Experimental Unit

- Key: (1) Heating Coil;
 (2) Slaggy;
 (3) Wood Chips;
 (4) Rocks;
 (5) Thermocouples;
 (6) Steel Diaphragm with Holes;
 (7) Mirror Galvanometer;
 (8) Thermostat.

In order to determine θ_{cp} it was assumed that the temperature of the air moving in the pores changes monotonically, that is, smoothly. In the tests temperature was recorded in three sections. Based on the three measured values of pore temperatures a curve (parabola) was drawn to establish the dependence $\theta = f(y)$ (θ is the air temperature in the pores and y is the coordinate). θ_{cp} was determined by the formula

$$\theta_{cp} = \frac{1}{H} \int_0^H f(y) dy = \frac{1}{3} a + \frac{1}{2} b + c, \quad (6)$$

where H is the elevation of the layer in the experimental unit;
 $a = 2(\theta_1 + \theta_3) - 4\theta_2$; $b = 4\theta_2 - \theta_1 - 3\theta_3$; θ_3 is average air temperature in the

pores in the lower measurement section of the tube; θ_2 is the same for the middle section; θ_1 is the same for the top section.

The average temperature in the measurement sections was determined by readings from the five thermocouples. The readings on one plane differed from one another, a result of the uneven movement of air on a cross-section of the experimental unit. Losses from the unit at the input and outlet were not taken into account in processing experimental results (see Figure 1). One of the tests was made without the steel diaphragm to determine the effect of losses at the input.

The diaphragm was replaced by a grid with cell dimensions of 20 x 20 centimeters. The results showed no significant differences. In all likelihood losses at the input do not exceed the precision of measurement of losses in the tests.

Losses at the outlet were estimated by calculation, which showed that losses at the outlet were less than the lifting force contained in the exit cone 2-3 hours after the beginning of the experiment. The tests were made with stones with average effective diameters of 10.6 and 19 centimeters. The average effective diameters were determined by reduction to the diameter of an equal-sized sphere. The porosity of the medium in the tests varied from 0.42 to 0.47.

The tests results are shown in Table 1 (partially) and in Figure 2. The average values of test results in the range of Reynolds number from 10 to 50 are described by the equation

$$f_p = \frac{4.30}{Re} + 0.85. \quad (7)$$

In Lev's formula [5] for determining drop of pressure in a layer the following values of the coefficient of hydraulic resistance are recommended: for $Re < 10$, $f_p = 100$; $Re = 50$, $f_p = 5$; $Re = 100$, $f_p = 1.2-1.3$; $Re \geq 1,000$, $f_p \approx 0.8-1.2$. It is apparent that the value of the coefficient of resistance for $Re = 50$ according to Lev's data is half the size of the same figure computed according to formula (7). In our opinion, the increase in resistance of the porous medium to air movement under conditions of natural convection is caused by strong cross-shifting of flowing air because the reason for the movement is heat exchange between the air and the faces of the cleavages. At some moments in time it is even possible for a closed circulation to form in certain pores, which reduces the live sections of the channels. Moreover, errors are possible in the tests themselves. First, the pores which we selected from the whole set are random ones. The flow of air in these pores and its temperature may not be typical of all phenomena in the particular section of the tube at any particular moment. Second, the introduction of measuring instruments (anemometers, mercury thermometers) into the flow disturbs the established regime of air current in the tube. Third, the porosity of the medium varied in the tests (from 0.42 to 0.47).

Table 1

θ (deg)	ΔT_{cp}	$\frac{1}{\beta} = \frac{1}{273 + \theta}$	$\gamma = \gamma_0(1 + \beta \Delta T_{cp})$	ϵ_{im}^*	$\epsilon_{im}^* \Delta T_{cp}$	ϵ	$\frac{\epsilon_{im}^* \Delta T_{cp} d^2 m^2}{\rho (1 m)^2}$	$Re = \frac{d v}{\nu_{air} (1 m)}$	Hydraulic diameter (Remarks)
41.76 44.1 49	44.52	0.00301	$18.8 \cdot 10^{-4}$	0.01325	0.59	0.0256	15.8	36.5	m 0.15 K 9.81 m/sec d 106 cm
6.96 8.4 10.9	8.78	0.00338	$15.36 \cdot 10^{-4}$	0.0149	0.131	0.00812	35.0	14.1	
24.2 37.7 47.2	37.04	0.0031	$17.88 \cdot 10^{-4}$	0.0137	0.508	0.0238	15.8	35.6	
101 31.64 27.46	43	0.00290	$20.06 \cdot 10^{-4}$	0.0128	0.551	0.0262	14.0	35.0	
30.58 27.10 49.68	31.48	0.00306	$17.11 \cdot 10^{-4}$	0.0135	0.426	0.0275	9.9	43.0	
56.24 28.84 43.28	35.31	0.00301	$18.78 \cdot 10^{-4}$	0.0133	0.470	0.0244	13.9	35.0	
57.24 13.60 16.26	21.31	0.00312	$17.65 \cdot 10^{-4}$	0.0138	0.244	0.021	11.7	32.0	
10.16 10.50 12.28	10.78	0.00337	$15.47 \cdot 10^{-4}$	0.01485	0.160	0.00812	42.7	14.0	
85 49.2 17.6	45.2	0.00300	$18.93 \cdot 10^{-4}$	0.0132	0.597	0.0225	20.7	32.0	
82.56 33.8 20.56	31.7	0.00302	$18.76 \cdot 10^{-4}$	0.0133	0.528	0.0225	18.3	32.0	
22.92 21.64 40.40	25.01	0.00311	$17.56 \cdot 10^{-4}$	0.0139	0.349	0.0221	12.5	33.7	m 0.15 K 9.81 m/sec d 106 cm
112.14 31.32 33.54	45.16	0.00284	$20.81 \cdot 10^{-4}$	0.0125	0.561	0.0272	13.4	35.0	
70.5 49.1 34.1	40.17	0.00288	$19.30 \cdot 10^{-4}$	0.0127	0.510	0.0302	10.0	31.5	
0.65 2.30 8.40	1.02	0.00339	$15.32 \cdot 10^{-4}$	0.0149	0.0598	0.0113	14.8	35.1	
1.8 5.6 15.4	7.1	0.00331	$15.65 \cdot 10^{-4}$	0.0147	0.105	0.0136	17.8	11.7	
2.81 5.08 14.65	6.3	0.00328	$16.18 \cdot 10^{-4}$	0.0145	0.091	0.0131	16.7	36.9	
3.2 2.9 15.2	5.0	0.00333	$15.80 \cdot 10^{-4}$	0.0147	0.0735	0.0129	14.2	39.1	

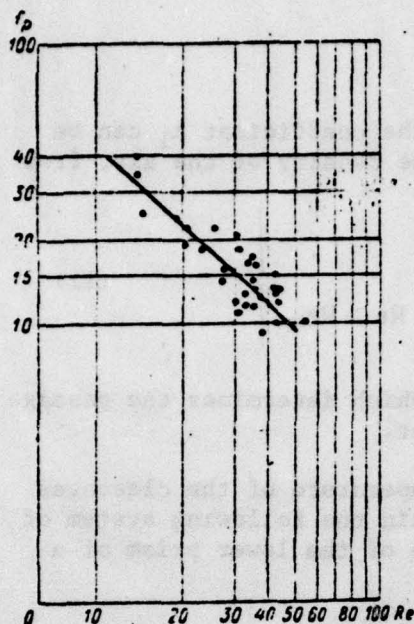


Figure 2. Dependence of Coefficient of Resistance of Porous Medium on Reynolds Number (Test Data)

It should be noted that using small values for the coefficient of resistance in calculating the thermal regime of the lower prism of rock-fill dams yields rapid changes in the temperature of the prism which are not observed in practice. This is especially true when the coefficient of turbulent filtration (b_0) is small.

The coefficients of permeability (k) and turbulent filtration (b_0) of the porous medium corresponding to the results of our experiments are determined from equation (7) by the following dependences:

$$\left. \begin{aligned} k &= \frac{d^3 m^3}{3100(1-m)^2} \\ b_0 &= 0.85 \frac{(1-m)^2}{dm^3} \end{aligned} \right\} \quad (8)$$

These are correct for a porous medium with effective diameters of more than 10 centimeters. Thus, experimental investigation determined the coefficients needed to solve the problem of nonlinear filtration of air in large-pore media.

2. Statement of the Problem and Method of Solving It

2. Statement of the Problem and Method of Solving It

Work [8] obtains an equation of the following type for determining air movement in porous media with natural convection:

$$\frac{\partial}{\partial x} \left(k_1 \frac{\partial \psi}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_1 \frac{\partial \psi}{\partial y} \right) = \frac{\partial (m \gamma \Delta T)}{\partial x}, \quad (9)$$

where ψ is the flow function. $k_1 = \frac{v}{k}$.

The mass velocities along the coordinate axes are expressed through the flow function by the formulas:

$$\frac{x \rho}{\tau \rho} = u, \quad \frac{y \rho}{\tau \rho} = v \quad (10)$$

where ρ is air density and u and v are a projection of the velocity vector on axes OX and OY .

It was assumed in deriving equation (9) that pressure losses are proportional to mass velocity in the first degree, that is, coefficient k does not depend on velocity. It can be shown that equation (9) is also proper where coefficient k_1 is a function of velocity.

In the latter case, in conformity with [9] the coefficient k_1 can be determined, with due regard for change in the density of the air, from the expression:

$$k_1 = f(\rho w) = \begin{cases} \frac{\mu}{\rho k}, & \text{при } Re < Re_{kp}; \\ \frac{1}{\rho} \left(\frac{\mu}{k} + b_{\mu} |\rho w| \right), & \text{при } Re \geq Re_{kp}. \end{cases} \quad (11)$$

where Re_{kp} is the critical Reynolds number which determines the passage of the air current from one regime to another.

Considering the equation for the average temperature of the cleavages of the fill and the air in the pores we obtain the following system of equations for determining the thermal regime of the lower prism of a rock-fill dam:

$$\frac{\partial t}{\partial \tau} = a \left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} \right) + \frac{\alpha_v}{c_{06}'} (t - \theta); \quad (12)$$

$$\frac{\partial \theta}{\partial \tau} - \frac{1}{\rho m} \frac{\partial \psi}{\partial y} \frac{\partial \theta}{\partial x} - \frac{1}{\rho m} \frac{\partial \psi}{\partial x} \frac{\partial \theta}{\partial y} = \frac{\alpha_v}{c_{06} m} (t - \theta); \quad (13)$$

$$\frac{\partial}{\partial x} \left(k_1 \frac{\partial \psi}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_1 \frac{\partial \psi}{\partial y} \right) = - \frac{\partial (\gamma^2 m \theta)}{\partial x}, \quad (14)$$

where t is the average temperature of the cleavages of the fill; a is the coefficient of temperature conductivity of the fill (disregarding convection); α_v is the volumetric coefficient of heat exchange; c_{06} is the volumetric heat capacity of the fill; c_{06}' is the volumetric heat capacity of the air; t is time.

The boundary and initial conditions of equations (12), (13), and (14) were discussed in detail in [8]. So with the exception of certain refinements we will not cite them fully here. When determining the heat flow from the lower prism toward the line of its contact with other air-permeable materials a coefficient of transverse convective heat conductivity must be introduced (by analogy with forced convection). For rocks in natural regimes M. E. Aerov and N. N. Umnik consider the values of the coefficients of transverse and longitudinal heat conductivity to be close and propose the following dependence to determine it:

$$\lambda_1 = \lambda_{0k} + B \lambda_s Re Pr, \quad (15)$$

where $\lambda_{0k} = 10.5$ is the coefficient of convective heat conductivity of the air with laminar current; λ_s is the coefficient of heat conductivity of the air; $Pr = c_p \alpha / \lambda_s$ is the Prandtl number; $Re = 4w/F$ is the Reynolds number; F is the area of the surface of particles in a unit of volume of the fill; B is the experimental constant.

The boundary conditions for equations (13) and (14) ($d\psi/dn = 0$ and $\theta = t_{\text{nap}}$) are more strictly realized at 4-5 meters from the daylight surface of the

lower prism because the influence of the temperature of the air moving out of the lower prism of a rock-fill dam is little felt here.

The transfer of the boundary conditions of equations (13) and (14) by the indicated distance corresponds to introducing, on the permeable layer of the lower prism, a fictitious porous layer with permeability equal to that of the fill but with zero volumetric heat capacity. On the surface of the fictitious layer, where $d\theta/dx = 0$, the condition $d\psi/dn$ is strictly realized. This follows from the orthogonality of the harmonic functions which satisfy equation (14) without the righthand part.

The system of equations (1) was used to determine the thermal regime of a triangularly shaped lower prism (Figure 3) with an initial temperature of 0 degrees C. The boundary conditions of the problem are shown in detail in Figure 3. It was assumed that, as functions of coordinates, changes in the density, specific weight, viscosity, and dilation of the air in the pores would not play a significant part in determining the velocity.

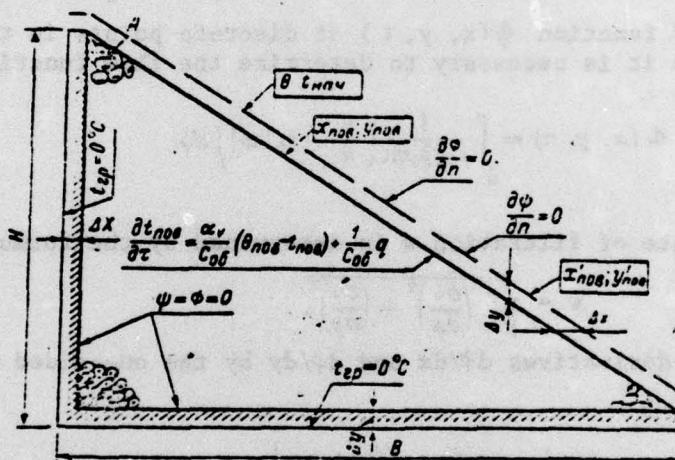


Figure 3. Diagram of the Calculation of the Thermal Regime of a Triangular Lower Prism ($B = 38\text{m}$; $H = 21\text{ m}$)

Then equations (13) and (14) of system (1) take the form:

$$\frac{\partial \theta}{\partial \tau} + \frac{1}{m} \frac{\partial \psi}{\partial y} \frac{\partial \theta}{\partial x} - \frac{1}{m} \frac{\partial \psi}{\partial x} \frac{\partial \theta}{\partial y} = \frac{\alpha_v}{c_{os} m} (t - \theta), \quad (15)$$

$$\frac{\partial}{\partial x} \left(\frac{1}{\rho_0} \left(\frac{\mu_0}{k} + b_0 |w| \right) \frac{\partial \psi}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{1}{\rho_0} \left(\frac{\mu_0}{k} + b_0 |w| \right) \frac{\partial \psi}{\partial y} \right) = -g \rho_0 m \frac{\partial \theta}{\partial x}, \quad (16)$$

where μ_0 , ρ_0 , and β_0 are the viscosity, density, and dilation of the air corresponding to the average temperature of the air moving in the pores.

The value of function $\phi(x, y, \tau)$ at discrete points on the surface of the fictitious layer was determined from condition $d\phi/dn = 0$ according to the following formula:

$$\phi_{n-1,j}^s = N\phi_{n,j}^s + N_1\phi_{n+1,j-1}^s \quad (23)$$

where

$$N = 1 / \left(1 + \frac{\Delta x \sin \alpha_n}{\Delta y \cos \alpha_n} \right); \quad N_1 = \frac{\Delta x \sin \alpha_n}{\Delta y \cos \alpha_n} / \left(1 + \frac{\Delta x \sin \alpha_n}{\Delta y \cos \alpha_n} \right).$$

The solution to equation (17) was considered found if the difference of the two investigation approximations satisfied the condition:

$$|\phi_{n,j}^s - \phi_{n,j}^{s-1}| \leq \varepsilon, \quad (24)$$

where ε is a given comparison constant.

For known values of function $\phi(x, y, \tau)$ at discrete points in the domain under consideration it is necessary to determine the flow function by the following equation:

$$Q(x, y, \tau) = \int_0^{\psi} \frac{1}{\rho_0 g \rho_0 m} \left(\frac{\mu}{k} + b_0 |\omega| \right) d\psi. \quad (25)$$

In this case the rate of filtration w is determined by the formula

$$w = \sqrt{\left(\frac{\partial \psi}{\partial x} \right)^2 + \left(\frac{\partial \psi}{\partial y} \right)^2}.$$

We approximate the derivatives $d\phi/dx$ and $d\phi/dy$ by the one-sided spatial differences, namely

$$\left. \begin{aligned} \left(\frac{\partial \psi}{\partial x} \right)_{n,j} &= \frac{\psi_{n,j} - \psi_{n-1,j}}{\Delta x}; \\ \left(\frac{\partial \psi}{\partial y} \right)_{n,j} &= \frac{\psi_{n,j} - \psi_{n,j-1}}{\Delta y}. \end{aligned} \right\} \quad (26)$$

We assume that $\phi_{n-1,j}$ and $\phi_{n,j-1}$ are known and do not depend on the value $\phi_{n,j}$. Then, substituting (26) into (25) we perform the integration within the bounds of the discrete point with coordinates $x = n\Delta x$ and $y = j\Delta y$ [1].

As a result we obtain the following algebraic equations:

a) for $c > 0; \Delta = 4ac - \eta^2 > 0$

$$\begin{aligned} g \rho_0 m \phi_{n,j} &= \frac{\eta}{k} \psi_{n,j} + \frac{b_0}{\rho_0} \left[\frac{(2c\psi_{n,j} + \eta)}{4c} \sqrt{c^2 \psi_{n,j}^2 + \eta \psi_{n,j} + a} + \right. \\ &\left. + \frac{(4ac - \eta^2)}{8c \sqrt{c}} \operatorname{Arsh} \left(\frac{2c\psi_{n,j} + \eta}{\sqrt{\Delta}} \right) - \eta \frac{\sqrt{a}}{4c} - \frac{(4ac - \eta^2)}{8c \sqrt{c}} \operatorname{Arsh} \frac{\eta}{\sqrt{\Delta}} \right]; \end{aligned} \quad (27)$$

b) for $c > 0$; $\Delta = 0$.

$$g_{\tau_0}^2 m \Phi_{n,j} = \frac{\gamma_0}{k} \psi_{n,j} + \frac{b_0}{\rho_0} \left[\frac{(2c\psi_{n,j} + \gamma_1) \sqrt{c\psi_{n,j}^2 + \gamma_1\psi_{n,j} + a} - \gamma_1 \sqrt{a}}{4c} \right], \quad (28)$$

where γ_0 is the kinematic viscosity coefficient of the air corresponding to the average temperature of the air moving in the pores

$$c = \left(\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} \right);$$

$$\gamma_1 = -2 \left(\frac{\psi_{n-1,j}}{\Delta x^2} + \frac{\psi_{n,j-1}}{\Delta y^2} \right);$$

$$a = \left(\frac{\psi_{n-1,j}^2}{\Delta x^2} + \frac{\psi_{n,j-1}^2}{\Delta y^2} \right),$$

where Arsh is the inverse value of the main hyperbolic sine.

To simplify the calculation of formulas (27) and (28) the ratios below may be used:

$$\left. \begin{aligned} \text{Arsh}(-z) &= -\text{Arsh } z, \\ \text{Arsh}(z) &= \ln(z + \sqrt{z^2 + 1}). \end{aligned} \right\} \quad (29)$$

In this case $\ln(z + \sqrt{z^2 + 1})$ is a natural logarithm

The solution to equations (27) and (28) must be begun from the lower left corner. In this case $\psi_{n-1,j}$ and $\psi_{n,j-1}$ are determined from the boundary conditions and do not in fact depend on $\psi_{n,j}$. Thus, the values of η and α when determining the next value of the flow function at a discrete point are always definite. The solution to equations (27) and (28) can be found using one of the methods of approximate solution of algebraic equations. The flow functions on the surface of the fictitious layer are determined by equation (23) as the result of a corresponding substitution of $\Phi(x, y, \tau)$ for $\psi(x, y, \tau)$.

The solution for linear filtration on condition $b_0 = 0$ is determined from equations (27) and (28) directly.

The numerical values of the parameters included in the calculation dependences were taken to be the following:

$d = 0.3 \text{ m};$	II $\left\{ \begin{aligned} k &= 3 \cdot 10^{-6} \text{ m}^2; \\ b_0 &= 0; \end{aligned} \right.$
$m = 0.35;$	$\gamma_0 = 4.79 \cdot 10^{-2} \text{ m}^2/\text{hour};$
$\rho_0 = 1/273 \text{ 1/degree};$	$g_0^2 = 9.81 \text{ m/sec}^2;$
$B = 38 \text{ m};$	$\mu\rho = 6.19 \cdot 10^{-2} \text{ kg/hr/m}^2;$
$H = 21 \text{ m};$	$C_p = 0.24 \text{ gcal/kg} \cdot \text{degree};$
I $\left\{ \begin{aligned} k &= 4.5 \cdot 10^{-6} \text{ m}^2; \\ b &= 0; \\ b_0/\rho_0 &= 200 \text{ 1/m}; \\ b_{of\rho_0} &= 500 \text{ 1/m}; \end{aligned} \right.$	$C_{oc} = 0.34 \text{ gcal/m}^3 \cdot \text{degree};$
	$\lambda_b = 2.1 \cdot 10^{-2} \text{ gcal/m} \cdot \text{hour} \cdot \text{degree};$
	$F = 17.5 \text{ m}^2;$

* Meters per hour squared were used for calculating acceleration of gravity.

$$\begin{aligned}
B\lambda &= 0.076; & t_{\text{ноч}} &= 0^\circ \text{ C.}; \\
a &= 0.002 \text{ m}^2/\text{hour}; & t_{\text{рп}} &= 40^\circ \text{ C.}; \\
\lambda_{\text{comp}} &= 0.7 \text{ gcal/m}\cdot\text{hour}\cdot\text{degree}; & \varphi &= 0.95; \\
C_{\text{ос}} &= 360 \text{ gcal/m}^2\cdot\text{degree}; & \varepsilon &= 0.001.
\end{aligned}$$

The volumetric coefficient of heat exchange was determined at discrete points by a calculation according to the formula

$$\alpha_{n,j} = \alpha_{n,j} / F \varphi,$$

where F is the area of the surface of cleavages in a unit of volume; φ is a coefficient which takes account of the decrease in heat exchange resulting from the internal gradient of temperatures in the cleavages,

$$\alpha_{n,j} = \frac{\lambda_a}{d} \left[2 + 0.6 \left(\frac{C_p w_{n,j}}{\lambda_a} \right)^{1.3} \left(\frac{10.7 d x_{n,j}}{\lambda_a} \right)^{1.2} \right] -$$

is the local coefficient of heat exchange; C_p is the heat capacity of the air at constant pressure; $w_{n,j}$ is the rate of filtration at the point with coordinates $x = n\Delta x$ and $y = j\Delta y$.

The time step ($\Delta \tau$) during calculations was variable and was determined from the stability of the explicit finite difference equation for average temperature of the cleavages of the lower prism [8]. The thermal regime of the lower prism was calculated in two variations (first variation when $k = 4.5 \cdot 10^{-6}$ square meters, $1-b_0 = 0$; $2-b_0 \rho_0 = 200$ l meter; $3-b_0 \rho_0 = 500$ l meter; second variation when $k = 3 \cdot 10^{-6}$ square meters and $b_0 = 0$). All other parameters remained unchanged.

The results of the calculations are represented in Figure 4 in the form of graphs of the dependence of change in the average temperature of the lower prism over time. With a decrease in the permeability coefficient (k) or an increase, where other conditions are equal, in the coefficient of turbulent filtration (b_0) the rate of change in average temperature of the lower prism decreases. Otherwise, it takes twice as much time to cool the lower prism to the same temperature where $b_0 \rho_0 = 200$ l meter ($k = 4.5 \cdot 10^{-6}$ square meters) as where $b_0 = 0$. This is related to the decrease in air velocity in the lower prism of the rock-fill dam (see Figure 5). Consideration of the nonlinearity of filtration leads to a more even distribution in time of the expenditure of air passing through the lower prism (Figure 5). It should be noted that there is no change in the qualitative picture of change in the temperature of the lower prism for any coefficients of turbulent filtration.

Conclusions

1. Empirical dependences were obtained for determining the coefficients of permeability (k) and turbulent filtration (b_0) in a large-pore medium.
2. A methodology is proposed for numerical solution to the nonlinear problem of air filtration in an isotropic large-pore medium.
3. Consideration of the nonlinearity of air filtration in pores under conditions of natural convection decreases the rate of change in the temperature of the lower prism of a rock-fill dam.

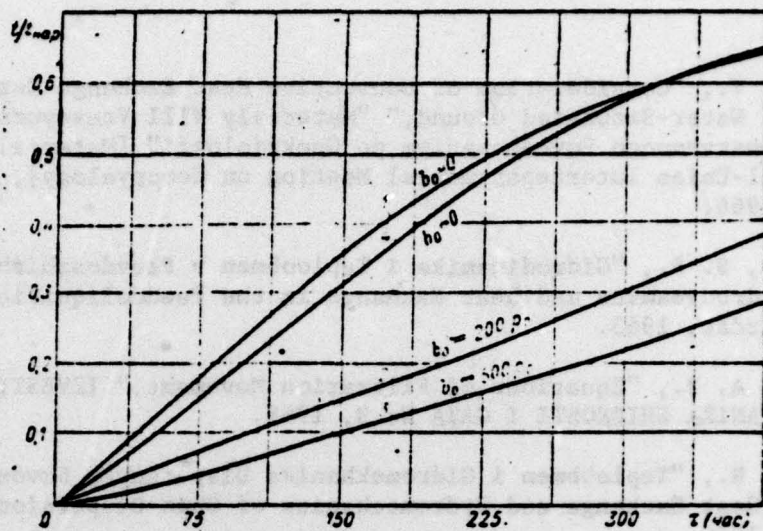


Figure 4. Change in Average Temperature of Lower Prism (B = 38 m, H = 21 m) over Time

Key: 1- $k=4.5 \cdot 10^{-6} \text{ m}^2$; $b_0=0$; 2- $k=4.5 \cdot 10^{-6} \text{ m}^2$; $b_0, p_0=200 \text{ l/m}^2$; 3- $k=4.5 \cdot 10^{-6} \text{ m}^2$; $b_0, p_0=500 \text{ l/m}^2$; 4- $k=3 \cdot 10^{-6} \text{ m}^2$; $b_0=0$.

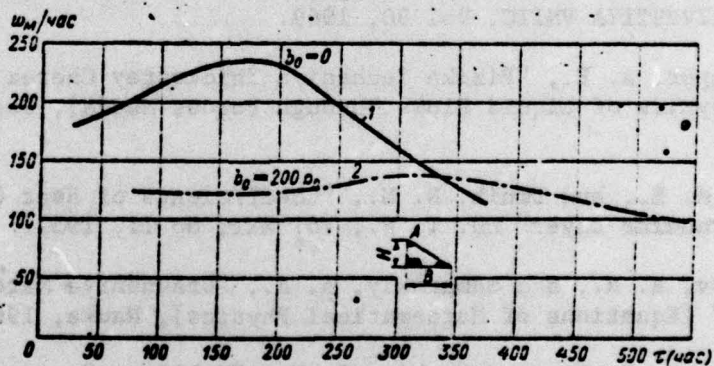


Figure 5. Change in Filtration Rate over Time at the Crest of the Lower Prism at Point A

Key: 1- $k=4.5 \cdot 10^{-6} \text{ m}^2$; $b_0=0$; 2- $k=4.5 \cdot 10^{-6} \text{ m}^2$; $b_0, p_0=200 \text{ l/m}^2$.

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